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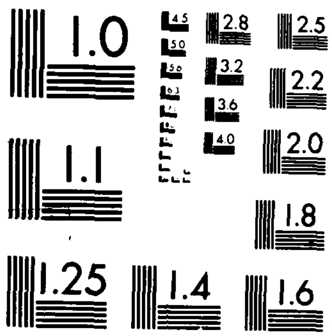
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REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-CS-12

FACTORS RELATED TO THE PERFORMANCE OF CONCRETE REPAIR MATERIALS

by

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GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS:

TOP — Montgomery Lock and Dam, Ohio River; freezing-thawing damage in service bridge support pier

BOTTOM — Montgomery Lock and Dam, Ohio River; repair on *service bridge support pier with high-quality air-*entrained concrete

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This report provides the status of information, including research needs, on the performance of materials containing polymers used to repair portland cement concrete. The following types of repair materials were covered: sealant type materials for repairing active cracks, and polymer adhesives, polymer mortars and concretes, and polymer-modified mortars and concretes for repairing spalls and dormant cracks and for placing overlays. This report is considered a first step in the process of developing performance tests and criteria and is intended to serve as a guide in selecting performance requirements, degradation factors, properties related to performance, and relevant existing test methods and their parameters.

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PREFACE

The investigation described in this report was conducted by personnel of the Building Materials Division (BMD) of the National Engineering Laboratory, National Bureau of Standards (NBS), Department of Commerce. The work was accomplished through a support agreement initiated by the US Army Corps of Engineers Waterways Experiment Station. The work and publication of the report were funded under Civil Works Research Work Unit 32272, "Evaluation of Existing Maintenance Materials and Methods." This work unit is part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program sponsored by Headquarters, US Army Corps of Engineers (HQUSACE). The Overview Committee of HQUSACE for the REMR Research Program consists of Mr. James E. Crews and Dr. Tony C. Liu. Technical Monitor for this study was Dr. Liu.

The investigation was performed under the general supervision of Dr. James R. Clifton, Leader, Inorganic Materials Group, NBS. The support agreement was managed by Mr. Richard L. Stowe who is the principal investigator for REMR Work Unit 32272. General supervision at WES was provided by Mr. Bryant Mather, Chief, Structures Laboratory (SL), Mr. James T. Ballard, Assistant Chief, SL, and Mr. John M. Scanlon, Chief, Concrete Technology Division (CTD). Program Manager for REMR is Mr. William F. McCleese, CTD. Problem area leader for the Concrete and Steel Structures Problem Area is Mr. James E. McDonald. This report was prepared by Dr. Lawrence I. Knab, NBS.

Messrs. John Beech, John Cook, Bryant Mather, Jules Panek, and Ray Schultz are gratefully acknowledged for their invaluable technical information and assistance. Messrs. Jim Clifton, Bob Mathey, Nick Carino, Richard Stowe, and Tony Husbands technically reviewed the report. Mses. Tonya Lewerenz, Kim Johnson, and Teresa Radcliffe located and organized references, and Ms. Denise Herbert typed the report.

COL Dwayne G. Lee, CE, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use $K = (5/9)(F - 32) + 273.15$.

FACTORS RELATED TO THE PERFORMANCE OF CONCRETE REPAIR MATERIALS

1. INTRODUCTION

1.1 Background

An important part of the U.S. Army Corps of Engineers' Repair, Evaluation, Maintenance, and Rehabilitation (REMR) research program concerns the repair of concrete. A large number of materials are currently available for repairing concrete. Often, however, their performance has been unsatisfactory. The lack of success with these materials has been attributed, at least in part, to an inadequate technical basis for their selection. For example, performance tests and criteria for selecting materials used to repair concrete are often not available. Because of a lack of criteria, each Corps office essentially operates independently with regard to selecting repair materials, often relying primarily on supplier information. Performance tests and criteria for repair materials need to be developed in order to improve the selection process and the field performance of these materials.

The National Bureau of Standards (NBS) initiated a study under the REMR program to provide the status of information related to the performance of concrete repair materials, based on information in the literature. The NBS work was concerned with materials for overlays and those for the repair of (1) active cracks (cracks expected to undergo further movement or extension), (2) dormant cracks (cracks unlikely to open, close, or extend), and (3) spalls.

1.2 Purpose and Scope

This report provides the status of information related to the performance of materials containing polymers used to repair portland cement concrete, including performance requirements, degradation factors, properties related to performance, and pertinent existing test methods and their parameters. Research needs related to developing performance tests and criteria are also given. The following types of repair materials which contain polymers were covered in detail: sealant type materials for repairing active cracks, and polymer adhesives, polymer mortars and concretes, and polymer-modified mortars and concretes for repairing spalls and dormant cracks and placing overlays.

This report is intended to be the first step in the process of developing performance tests and criteria for materials to repair concrete. The information in it can be used as a guide in identifying and selecting (a) the important performance requirements, degradation factors, and properties related to performance, and (b) pertinent existing test methods and their parameters to measure the properties related to performance.

In this study, the performance of repair materials after they are installed was of major concern. Though important to the proper functioning and durability of a repair material, other considerations including the design, installation, and repair methodology requirements, are excluded from this study. Information

relating to steel reinforcement, including protection, bond strength, and corrosion, is also excluded.

For active crack repairs, materials which are presently being used as joint sealants* are covered. It is assumed that the method (ACI 77a**, CST 82) used is to cut a suitably dimensioned recess along the line of the active crack and then seal it with an appropriate field-molded*** sealant, which adheres to the crack walls. Thus, the experience and technical information available on joint sealant materials for concrete can be applied to repair active cracks.

Grouting technology and materials, which may be applicable for the repair of cracks in concrete (e.g., see reference War 85), are not covered. Materials which "seal" the concrete and which can fill hairline cracks are also not covered.

2. PERFORMANCE APPROACH

The information on the performance of repair materials in this report is intended to serve as a guide in developing performance tests and criteria. One format (MaC 74) for developing quantitative performance criteria involves determining for each performance requirement† (e.g., withstand cyclic movement under in-service conditions) the following:

(1) A pertinent property related to performance (e.g., resistance to cyclical movement under specified degradation factors††),

(2) A quantitative criterion (e.g., specimen of sealant bonded to concrete substrate must withstand a certain number of specified cyclical movements performed under specified degradation factors),

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* Sealant - "any material used to seal joints or openings against the passage of solids, liquids, or gases" (ACI 77a).

** Citations in parentheses refer to references listed in References.

*** Field-molded sealant - "a liquid or semi-solid material molded into the desired shape in the joint into which it is installed" (ACI 77a). Primers and back-up materials used with joint sealants are not covered in this report - see references ACI 77a and PaC 84.

† Performance requirement - a qualitative statement of the performance required from a repair material (ASTM 82).

†† Degradation factor - any of the group of external factors (e.g., stress, weathering) that adversely affect the performance of a repair material (see ASTM 82 for further details).

(3) A test method conducted under specified degradation factors (e.g., use of cyclical tester with controlled environmental conditions), and

(4) A commentary providing an explanation of the reason for, and intent of, the criteria (e.g., cyclical test, though intended to simulate in-service movement, is an accelerated test and needs to be interpreted as such).

In order to provide information related to performance test methods and criteria as given in the above criteria format, the following information sources were initially considered:

(a) the past in-service performance of repair materials,

(b) research on (i) the effects of degradation factors on performance of repair materials, (ii) properties of repair materials that can be related to their performance, and (iii) test methods that can be used to measure these properties, and

(c) standards and specifications and their associated test methods, either existing, proposed, or under development, that can be used or modified to establish performance test methods and criteria.

Although some documentation of the in-service performance of repair materials exists, there is relatively little information relating material properties and their test methods to in-service performance. Due to this lack of information, source (a) was not emphasized in this report. Rather, sources (b) and (c) were emphasized because they were considered to be most meaningful in developing performance criteria.

Based on a review of the literature, including research, standards, and specifications, the following factors related to performance were identified for the repair material types considered:

- performance requirements

- degradation factors and their effects on the performance of the repair materials

- properties that can be related to performance and test methods and the parameters that can be used to measure these properties

- standards and specifications and their associated test methods that could either serve as interim criteria or be modified to reflect in-service conditions, degradation mechanisms, and performance.

After identifying the factors related to performance, their role and relative importance as related to developing performance tests and criteria were established wherever possible. Thus, the information presented

is considered a first step in the process of developing performance tests and criteria (see sections 3.3 and 4.3).

The work was divided into sealant materials used to seal active cracks and stiffer materials containing polymers used for overlays and the repair of spalls and dormant cracks.

This report will need to be updated as new information on repair materials becomes available.

3. SEALANT REPAIR MATERIALS FOR ACTIVE CRACKS

3.1 Generic Types of Sealant Materials

References ACI 77a and PaC 84 cover in detail the many generic types of sealant materials, including their properties, standards and specifications, and applications. (Section 1.2 describes which types of sealant materials are covered in this report.)

3.2 Research on Degradation Factors, Properties, and Test Methods Related to Performance of Sealant Materials

3.2.1 Laboratory Investigations

Karpati has conducted a number of laboratory studies on one-part chemically curing silicone building sealants and a two-part polysulfide building sealant, generally using aluminum substrates (e.g., Kar 72a, Kar 72b, Kar 73). Her important findings and conclusions include the following:

(a) She has developed methods for predicting* the failure of the silicone (Kar 72b) and polysulfide (Kar 73) sealants based on laboratory tensile testing. According to her (Kar 79), the factors that govern the behavior of sealants are: "stress, strain, temperature, rate of deformation, humidity, air, light, type and condition of substrate, and presence of water or chemicals. Of these, stress, strain, deformation rate, and temperature are of primary importance. They have to be known simultaneously in describing a material at any given age, humidity, substrate condition, etc. Consequently, these four factors must be included in any test method devised to measure mechanical properties, while the other variables must be kept constant at values considered to be realistic."

(b) In an investigation of the tensile properties of a one-part chemically curing silicone sealant, she (Kar 72b) observed the material to be "temperature independent in the region important to sealants, with

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* See references for details on how predictions were made. For example, extrapolation was used to predict extensibility (Kar 72b).

some deviation from the rule near the crystallization temperature under high strain."

(c) "Cyclic tests provide the best representation of the conditions to which sealants are subject in practice" (Kar 80b). Cycling tests, however, are complex. Karpati concluded that "the laboratory cycling experiments can be connected to the tensile results and, therefore, there is a rational way to derive the cycling conditions" (Kar 80b). (See reference Kar 80b for details on cycling tests, tensile tests, and sealants used.)

Matsumoto, Ono, and Maruichi (MOM 80) used cycling compression-extension testing to quantitatively determine the "fatigue process of a sealant, based on resilient energy." "Resilient energy" was calculated based on tensile testing of specimens which had undergone a prefixed number of movement cycles. The authors investigated 2-part polysulfides, 1-and 2-part silicones, and 1-and 2-part polyurethanes all tested on aluminum substrates. From their results, they developed a rational method of obtaining the movement capability of sealants.

The relationship of a number of properties, including those derived from tensile testing, to accelerated aging tests was investigated (LeR 72) for a number of polysulfide-based sealants on concrete* substrates. The authors concluded that the changes in properties before as compared to after aging were "of different orders and sometimes even followed divergent directions." They also concluded that a correlation between accelerated aging tests and outdoor exposure tests is needed to quantitatively predict service life. They saw the need to define a "coefficient of accelerated aging," which would be related to local climatic conditions and which would "be obtainable by comparing such criteria as strain energy or toughness, which are best suited for predicting the performance of a sealant under working conditions."

Spells and Klosowski (SpK 85) have performed preliminary studies of (1) the effects of temperature and accelerated weathering (including ultraviolet (UV) radiation and condensation to simulate rain and dew) on the modulus (amount of tensile stress required to produce a given strain), and (2) the effect of accelerated weathering on the number of shear cycles (at -18°F) to failure. Polyurethane, polysulfide, and low-modulus silicone sealant types were included in their study. Among their conclusions were:

(a) "All samples tested showed a decrease in the number of shear cycles with simulated weathering or lower temperatures except for the low-modulus silicone." They attributed this decrease to the "change in the sealant's rubber or modulus property with temperature or aging," and

* Text unclear as to whether mortar or concrete substrates were used.

(b) "... modulus testing provides a tool that is useful in measuring changes in rubber properties and in matching the sealant to the performance requirements."

Karpati (Kar 78b) developed a test method for evaluating the resistance of a sealant specimen to water immersion. The test included tensile testing a sealant specimen while it was continually immersed in water. She stated that the test "was developed for performance testing of sealants while immersed, such as would occur in swimming pools and water reservoirs." Results were presented for a two-part polysulfide sealant cast on aluminum substrates and cement-mortar substrates.

3.2.2 Investigations Involving Outdoor Exposure

Karpati has conducted a number of studies* (Kar 80a, Kar 84a, Kar 84b, Kar 85) involving outdoor exposure with strain-cycling racks or manually operated vises. Her investigations on outdoor exposure have included one-part chemically curing silicone and two-part polysulfide building sealant types, both tested on aluminum substrates. Her findings and conclusions include:

(a) For the sealants studied, strain cycling was determined to be the most important degradation factor:

(i) "Strain cycling movement is the predominant factor that causes failure during weathering of a one-part chemically curing silicone sealant; outdoor weathering alone is negligible ....

For this particular silicone sealant, heat aging cannot be used to accelerate weathering since the properties improve instead of deteriorate, as on outdoor cycling. This is probably due to the establishment of a better bond between the sealant and the substrate or primer" (Kar 80a).

(ii) Strain cycling is the "most important factor in test methods intended to evaluate their (two-part polysulfide sealants) performance" (Kar 84b).

(b) For a two-part polysulfide sealant, three stages of permanent deformation associated with the polysulfide sealant exposed outdoors on manually operated vises were recognized (Kar 85).

(c) In addition to visual observation of failure progression caused by strain cycling, laboratory tensile testing was used to investigate the properties of outdoor exposed specimens (Kar 80a, Kar 84b, Kar 85).

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* Also see the recent submission by Karpati: "Laboratory Fatigue Test of a Two-part Polysulfide Sealant Correlated to Outdoor Performance."

(d) She tested specimens of a two-part polysulfide sealant on manually operated vises (Kar 78a, Kar 85) which were exposed outdoors and had movements imposed on them. The results obtained using the vises were compared with previous results from a strain-cycling rack (KSS 77). She concluded that "The results show that the vises can replace the strain-cycling rack that imitates the performance of sealants in building joints. This work is therefore a step forward in establishing a link between outdoor performance and laboratory tests of sealants, since the vises can be used in the laboratory, with some changes in the conditions imposed."

(e) A relatively quick outdoor exposure screening test was developed (Kar 84a) which eliminated unsatisfactory silicone sealants within two months. The test was demonstrated with 13 silicone sealants on aluminum substrates (the silicone types were not given). She indicated that the test could also be used to "determine whether a primer is required and whether there are batch-to-batch variations in a material."

Beech (Bee 85) reviewed various types of apparatuses "designed to impose upon the samples a simulation of joint movement, simultaneously with exposure to the weather." He indicated that the imposed movement is "usually actuated by temperature and radiation changes induced by weather." He cited a number of studies using such apparatuses, including Karpati's strain cycling rack (KSS 77), which has already been discussed, and studies by Fry and Whitney (FrW 79) and Burstrom (Bur 80), which are discussed below.

Fry and Whitney (FrW 79) investigated the effects of two years of natural weathering on a range of sealants using a cyclic movement test rig. The following sealant types were investigated: acrylic latex, acrylic solvent-based, one- and two-component polyurethanes, one-and two-component polysulphides, and silicone. They evaluated sealants in butt joints between aluminum surfaces and in shear joints between glass and aluminum. The glass-sealant interface in the shear joint was exposed to sunlight and the sealant was continuously in contact with water. They concluded that the "cyclic movements tester has proved to be a useful tool by illustrating the relative differences in performance between different types of building sealants ..." and stated that "Exposure of the sealants without cyclic movement was not sufficient to evaluate reliably sealant durability."

Burstrom (Bur 80) investigated in the laboratory the effects of temperature (heat), humidity, akaline water, ultraviolet light, and ozone on a number of different sealant types. He also used outdoor tests, which involved exposure to natural aging (i.e., natural climate combined with joint movements). The appearance and shapes of tensile stress-strain curves of specimens subjected to certain testing conditions and exposures were studied; the specimens were elongated to 100 percent strain at 2°C, at which point the stress relaxation was measured for about 10 min. (See reference Bur 80 for the details of the sealant types and testing conditions and exposures used, including the substrate types and the definition of "humidity".) Burstrom stated: "The temperature is the aging influencing factor that has been found to have the greatest effect on the deformation characteristics of the sealants. But it is impossible to

find a general connection between accelerated aging in heat and natural aging for different types of sealants." As an example of the difficulty in making universal conclusions for heat aging effects, he cited that a soft polysulfide sealant became softer after heat aging; this is contrary, he said, to the expected trend of hardening after heat aging. However, this same material turned harder in the outdoor experiment. Burstrom did, however, demonstrate that in special cases it was possible to get a correlation between outdoor-stored and heat-aged specimens. He attributed the correlation to the heat-aging effect having clearly dominated the effects of other factors.

The Bureau of Reclamation (Joh 58) also developed an outdoor apparatus for evaluating the performance of sealing materials used in contraction joints of concrete canal linings. The apparatus can be used to study simultaneously the effects of aging, temperature, moisture (including alternate wetting and drying), and stress due to continuous expansion and contraction of the joint. Some results using the Bureau of Reclamation's apparatus are given in reference SeM 61.

Beech and Turner (BeT 83b) investigated the curing characteristics in the laboratory and under natural exposure of a range of elastomeric building sealants, including one-part polysulfides, one-part polyurethanes, and one-part silicones. Two properties were used to measure degree of cure: tack-free time and hardness. They stated: "Temperature, relative humidity, and ultraviolet light were noted to have an interactive effect on cure, although the influence of these factors varied between the different sealant types studied." (See reference BeT 83b for the details of the curing characteristics.)

3.2.3 Standards and Specifications and Their Test Methods and Pertinent Parameters

Sealant specifications, standards, and test methods have been reviewed extensively, including those references which cover:

(a) more than one generic type of sealant (ACI 77a, AFM 83, Bee 80a, Bee 80b, Bee 85, Eva 80, EvT 85, PaC 84, Pan 76, Pan 81, Sei 81)

(b) one generic type of sealant (e.g., oil and resin base - Bec 76; solvent-base acrylic - Mra 76, Wat 76; chlorosulfonated polyethylene - Pai 76; polysulfide - Bol 76, PPS 76; urethane - EvG 76, EvG 81; silicone - Klo 80; polyvinylchloride/coal tar type ("pitch PVC") - McC 81).

Table 1 lists U.S. Federal (1A) and ASTM (1B) specifications and standards for sealants for use with concrete; in some cases the requirements related to movement* are also shown. The reader is referred to the specifications and standards (table 1), their references, and also to reference PaC 84 with regard to test methods, requirements, etc.

Because of the extensive review of sealant specifications, standards, and test methods (see references above), only a limited number of references considered to be particularly relevant are discussed below.

Evans (Eva 80) has reviewed the evolution of sealant durability testing, and with Torporcer (EvT 85), has provided a report of recent International Standards Organization (ISO) efforts in developing an international durability test method.

Beech (Bee 85) has reviewed and compared test methods to assess the movement capability of building sealants. Included were test methods taken from national and international standards. He stated "The ability of a joint sealant to withstand repeated extension/compression movements is, together with its durability, the most important performance characteristic." He discussed various in-service degradation factors, including water, UV radiation, and variable temperature, in relation to laboratory cyclic extension/compression testing. He concluded with regard to cyclic testing that "A variety of test methods intended to assess the capability of joint sealants to withstand cyclic movement is available. These differ markedly in the manner in which they incorporate salient factors from service."

With regard to the influence of cure on sealant performance, Beech (Bee 85) stated: "It is apparent that the degree of cure markedly affects physical properties such as tensile modulus, elastic recovery and hardness, which are related to performance in service." In addition, Beech and Turner (BeT 83a) concluded that "Sealant testing should evaluate the effects of cyclic joint movement and climatic conditions during sealant cure as well as in the fully-cured condition."

Panek and Cook (PaC 84) state that "The major sealant reference standards include cyclic tension and compression testing ..." They review some of the test devices that have been developed for cyclic tension and compression testing.

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* Note that, according to J. Panek (private communication-June 1986), the "maximum total joint movement" as defined and explained in the Federal specifications (table 1A) is not consistent with the latest methods of expressing movement capability and can lead to misinterpretation and improper joint design. For further clarification, see sections 2.3 and 5.1 of reference PaC 84. Also see reference PaC 84 for estimates of movement capability for some generic types of sealants.

Beech (Bee 85) in discussing weathering and aging factors stated: "The inclusion of weathering and/or aging is evidently of great importance in any realistic prediction of movement accomodation of sealants in service ..." but stated that "we are still far from achieving a consensus regarding acceptable laboratory procedures for simulating aging and weathering in the laboratory."

Several studies have investigated movements in building joints (e.g., BeT 83a, KaS 76a, KaS 76b); Beech and Turner (BeT 83a) discussed the relevance of current sealant test methodology in relation to observations of the amount, rate, and pattern of cyclic joint movement in buildings.

3.3 Factors Affecting Performance of Sealant Materials

Table 2 is based on a number of references (e.g., ACI 77a, AFM 83, ASTM 82, Bee 80a, ISO 75, ISO 84, PaC 84 and the Federal and ASTM specifications and standards listed in table 1). Table 2 lists performance requirements, degradation factors, and properties related to performance for sealant type materials used to repair active cracks in concrete. Although the information in table 2 covers many situations, it is not comprehensive. Therefore, each structure to be repaired needs to be carefully analyzed on an individual basis, choosing the appropriate performance requirements, degradation factors, and properties related to performance from table 2, and adding any performance requirements, degradation factors, and properties related to performance as encountered or needed. The properties related to performance are considered preliminary because their relationship to in-service performance needs to be established.

Based on research references, standards, and specifications, a summary of the more important factors affecting performance is given. A statement of research needs related to developing performance tests and criteria is also included. The information in the summary and information derived from additional research are considered a first step in the process of developing performance criteria and are intended to serve as a guide in selecting performance requirements, degradation factors, properties related to performance, and relevant existing test methods and their parameters. Although the summary and statement of research needs were based largely on literature pertaining to certain building sealants tested under certain conditions (see sections 3.2.1 and 3.2.2), the information in the summary as well as information derived from additional research should be applicable for active crack repairs using a variety of sealant classes, used in different types of concrete structures and their different environments. It is assumed that the method used is to cut a suitably dimensioned recess along the line of the active crack and then seal it with an appropriate field-molded* sealant, which adheres to the crack walls.

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* Field-molded sealant: "a liquid or semi-solid material molded into the desired shape in the joint into which it is installed" (ACI 77a).

3.3.1 Summary

1. The most important performance requirements are considered to be the ability of a sealant and its bond to its concrete substrate to withstand all in-service cyclical movements (e.g., extension and compression) while being subjected to the other in-service degradation factors (temperature, moisture, etc.) for the intended life of the repair. The most important group of test methods are considered to be those involving cyclical movement, where one or more degradation factors can be varied during testing.

   These degradation factors (movement, temperature, moisture, etc.) can have a major influence on performance, either acting alone or synergistically. With waterways structures, the role of moisture or temperature or both (water immersion, freezing and thawing, hydrostatic pressure, etc.) deserve special consideration.

   The effects of the rate and degree of curing on performance can also be important. For example, Beech and Turner (BeT 83a) state that a "shortcoming of current test methodology is that sealants are not subjected to cyclic movement during the cure phase" (see their discussion for details).

   Specimens consisting of a sealant adhered to two mortar or concrete substrates are considered more meaningful than specimens consisting of only sealant because (a) they can simulate the substrate surfaces and geometry of the repaired crack, and (b) failure by either adhesion or cohesion can be evaluated.

2. Other factors related to performance that need to be considered are:

- While the performance requirements, degradation factors, properties related to performance, and associated tests given in this section (3.3.1) are considered the most important, it is still necessary to consider all pertinent peformance requirements, degradation factors, properties related to performance, and associated test methods when developing performance tests and criteria (see table 2).

- The determination of the important degradation factors which affect performance can depend on the sealant types being considered. For example, the effect of heat aging can have completely different effects on performance, depending on the sealant type (see reference Kar 80a, where heat aging improved instead of degraded the properties of the silicone sealant tested).

- Special factors affecting in-service performance of sealants may need to be simulated including:

  - the substrate type and surface conditions (e.g., moisture) and the use of a primer

- the geometry (shape-factor) of the sealant in the joint.

3. Existing ASTM and U.S. Federal standards and specifications (table 1) and their test methods are useful in developing performance tests and criteria because the standards,specifications, and their test methods:

   (a) can serve as interim performance criteria until more relevant performance criteria are developed,

   (b) have the potential to be modified to simulate the in-service conditions (movement, temperature, etc.), degradation mechanisms, and performance of sealants used to repair active cracks in different types of concrete structures in a variety of environments, and

   (c) reflect, at least to some degree, the in-service performance associated with the particular sealant type or types for which they were developed.

   However, the existing ASTM and Federal standards and specifications and their test methods may not adequately simulate in-service conditions, degradation mechanisms, and performance because:

   (a) the test exposure conditions may not be closely related to the expected in-service conditions. For example, Beech and Turner (BeT 83a) discussed differences between test method exposure conditions and in-service conditions for buildings, including differences associated with the magnitude and rate of movement and the effect of curing.

   (b) the standards, specifications,and their test methods have not been systematically related to in-service performance.

4. Outdoor cyclical movement tests can provide valuable information on long-term performance. In addition, outdoor cyclical tests, such as that developed by Karpati (Kar 84a), have the potential for providing additional information including (a) screening sealants relatively rapidly (e.g., within two months for silicone sealants - Kar 84a), (b) simulating in-situ (as would occur in service) curing of sealants, and (c) determining if a primer is needed.

5. The use of simple, manually operated vises* (Kar 78a, Kar 85) have the potential to be used in outdoor and indoor sealant testing including (a) relatively rapid screening of sealants, (b) simulating in-situ (as would occur in service) curing of sealants, and (c) determining if a primer is needed.

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* Vise: "imposes movements on sealant specimens at arbitrarily chosen amplitudes and time intervals by manual adjustment" (Kar 85).

3.3.2 Research Needs

Consideration should be given to the following research needs:

1. The in-service conditions of the structure being repaired, including the active crack site, should be quantified. If possible, the characteristics (e.g., amplitude, rate*, frequency, number, duration, and sequence) of the cycles of the degradation factors (movement of active crack, temperature, moisture, ultraviolet light, etc.) that the structure experiences should be quantified.

   Environmental conditions (movement, temperature, etc.) could be represented by several "standard" environments, with each "standard" environment representing the environment in structures subjected to similar environmental conditions.

2. The order of importance of the degradation factors which occur in service should be established for each generic type of sealant.

   The degradation mechanisms occuring in service for each generic type of sealant should be identified and quantified. For example, see Karpati's description of the three stages of degradation of a two-part polysulfide (Kar 85). Indicators of degradation need to be identified which quantitatively define the degree of degradation and final failure.

3. Simple and rapid screening tests, which simulate in-service conditions, degradation mechanisms, and performance, should be developed. These tests could be conducted either in the laboratory or outdoors. Karpati's research (Kar 84a) provides an example of a relatively rapid outdoor screening test for silicones. Use of her manually operated vises (Kar 78a, Kar 85) could potentially simplify this outdoor screening test. Once developed, screening tests could also potentially be used to evaluate the effects of special factors, such as simulating in-situ (as occurs in service) curing and determining if a primer is needed. (Also see section 3.3.1.)

   Tests which can be performed both in the laboratory and in the field should be considered - they would be helpful in establishing the relationships between laboratory test results and in-service performance.

4. Analytical modeling** of sealants bonded to their concrete substrates should be conducted to determine the relative importance of the

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* "Rate" refers to the rate at which a degradation factor is occurring within a given cycle (e.g., rate of movement of active crack walls).

** For example, see reference Won 84.

factors affecting in-service performance (see section 3.3, including table 2).

5. Consideration should be given to investigating methods of predicting or estimating the long term behavior and field performance of sealants (e.g., the prediction of long-term behavior based on short-term tests). Several approaches to predict or estimate field performance are reviewed by Karpati (Kar 68), including "time-temperature superposition" and the "kinetic approach". Karpati has applied time-temperature superposition to her research (Kar 73).

6. The information in this section (3.3) together with ASTM E 632 (ASTM 82), should be used as a guide in:

   (a) modifying existing ASTM and Federal standards and specifications or developing new performance tests and criteria to quantitatively simulate the in-service conditions, degradation mechanisms, and performance of sealants used to seal active cracks in concrete,

   (b) systematically and quantitatively establishing the relationships of the results of the modified or newly developed performance tests to in-service performance, and

   (c) establishing performance criteria based on the performance tests and the relationships of their results to in-service performance.

   The order of importance of the properties which are related to in-service performance should be established when modifying or developing performance tests for each generic type of sealant.

   Care should be taken to insure that any accelerated testing simulates the in-service conditions, degradation mechanisms, and performance.

4. MATERIALS USED AS OVERLAYS AND TO REPAIR SPALLS AND DORMANT CRACKS

4.1 Generic Types of Repair Materials

A National Cooperative Highway Research Program (NCHRP) study (NCH 77) reviewed the use and performance of rapid-setting materials for patching portland cement concrete pavements and bridge decks. In this reference, patching materials were classified into eight groups:

(1) basically portland cement (e.g., Type III with or without admixtures, regulated set cement)

(2) other chemically-setting cements (e.g., high-alumina cements, magnesia-phosphate, but not calcium phosphate types)

(3) thermosetting materials (e.g., epoxy resins, polyesters)

(4) thermoplastics (e.g., sulfur, but not bituminous materials)

(5) calcium sulfate

(6) bituminous materials (e.g., hot-mixed dense-graded asphalt concrete, asphalt emulsions, cold-mixed cutback asphalts, and tars)

(7) composites (e.g., fibrous concrete)

(8) additives (i.e., materials used to alter characteristics of mixtures)

In addition to reference NCH 77, there are other references which contain information on different types of repair materials. These include (a) conventional portland cement concrete (e.g., DaD 34, Fel 56, Fel 60, Gil 65, NCH 79, NCH 82, Wes 60), (b) nonshrink or shrinkage compensating hydraulic cement mortars, concretes, and grouts (e.g., CoC 84, CuK 77), and (c) rapid-setting concretes and mortars (e.g., EaH 71, MSF 84).

This chapter is limited to the following types of repair materials containing polymers:

- polymer adhesives - a polymer either with or without a fine filler (e.g., ASTM C 881-78 (ASTM 78c) contains definition of filler for epoxy-resin-base bonding systems)

- polymer concrete* or polymer mortar* - a composite material in which the aggregate is bound together by a polymer binder.

- polymer-modified concrete* or polymer-modified mortar* (also referred to as polymer-portland cement concrete (ACI 77b)) - material "made by the modification of ordinary cement mortar or concrete with the polymer additives such as latexes, powdered emulsions, water-soluble polymers, liquid resins and monomers" (Oha 84).

Reference ACI 77b contains additional details on polymer mortars and concretes and polymer-modified mortars and concretes.

Polymer-impregnated concrete (see ACI 77b), bituminous materials, and repair materials containing sulfur are not covered in this chapter.

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* In this report, "concrete" refers to repair materials containing coarse aggregate, and "mortar" refers to repair materials containing fine aggregate (e.g., sand) but not coarse aggregate.

A number of combinations of applying repair materials containing polymers to portland cement concrete and mortar have been investigated (see section 4.2.1).

Factors affecting the performance of the bond of a repair material to its existing concrete substrate*, including the effects of temperature, duration of load application, and moisture, are emphasized. The effects of temperature, duration of load application, and moisture on certain properties of "plain" repair materials (i.e., excluding their concrete substrate) are also included. Other factors affecting the performance of repair materials containing polymers are not covered - the reader is referred to the voluminous literature on polymers used with concrete (e.g., ACI 68, ACI 73, ACI 77b, ACI 78, Bar 82, ICP 75, ICP 78, ICP 81, ICP 84, RIL 67).

4.2 Research on Degradation Factors, Properties, and Test Methods Related to Performance of Repair Materials

4.2.1 Bond of Repair Material to Its Concrete Substrate

There have been many investigations employing a variety of test methods to investigate the bond strength of repair materials to concrete. Table 3 lists the test methods used in the investigations reviewed in this report, with the methods classified as shear, tension, flexure (bending), thermal compatibility, and shrinkage. The test methods in the investigations (table 3) have been used to evaluate a number of applications of concrete repair materials, including bonding of:

(a) hardened concrete (or hardened mortar) to hardened concrete (or hardened mortar) using a polymer adhesive or polymer mortar,

(b) fresh concrete (or fresh mortar) to hardened concrete (or hardened mortar) using a polymer adhesive or polymer mortar,

(c) polymer-modified concrete (or polymer-modified mortar) to hardened concrete (or hardened mortar),

(d) polymer concrete (or polymer mortar) to hardened concrete (or hardened mortar).

In the investigations, various types of hardened concrete or mortar surfaces (to which the repair materials were adhered) were studied, including cast, sawn, or fractured surfaces. Prior to applying the repair material, some surfaces were specially treated with acid, sandblasting, etc.

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* "Concrete substrate" refers to the hardened (existing) portland cement concrete surface or surfaces to which the repair material is bonded. The repair material can be bonded above, below, or in between the concrete surface or surfaces repaired.

In some of the studies listed in table 3, degradation factors, such as temperature and moisture, were varied to evaluate their effect on the bond strength (see section 4.2.2).

A general comment on determining the bond strength of epoxy-resin adhesives to concrete, stated by Schutz (Sch 68) is: "that the tensile strength of a good epoxy adhesive will be in the order 10 to 20 times that of concrete. Most test procedures will not indicate the strength of the adhesive but will merely show the strength of the bonded concrete."

The different types of bond-related tests listed in table 3 are discussed below.

4.2.1.1 Shear Strength

The shear strength of the bond of a repair material to its concrete substrate has been investigated using several test methods: direct, slant, and "other" (table 3).

Kriegh (Kri 76), in comparing a number of test methods for determining the epoxy bond strength to concrete, presented arguments for the use of the "composite cylinder test" (i.e., the slant shear test):

> "As a means of evaluating the strength of the epoxy and the epoxy bond of hardened concrete to hardened or plastic concrete, the composite cylinder test has proved to be the most reliable and consistent of all other tests because it represents a condition closer to the actual use and failure mode of concrete. This is especially true when it is compared with those tests relying on the tensile strength of the concrete as a failure criterion.
>
> For example, the flexure beam test as modified for epoxy bond testing utilizes the tensile strength of the concrete as a basis for determining effective bond strength. Concrete is so weak in tension that steel is used in concrete to take tensile forces. Therefore, having a tensile bond strength greater than concrete is really not much of a requirement and actually has little meaning.
>
> The real value of concrete is in its compressive strength. If new or old concrete is to be effectively bonded to existing concrete with an epoxy adhesive, the adhesive must be formulated adequately to satisfactorily transfer all of the compressive forces the original and new concrete are expected to carry. The composite cylinder test measures the ability of the epoxy compound to do this."

Kriegh (Kri 76) concluded that the composite cylinder test could be used in evaluating the strength of concrete-to-concrete bonds, including evaluating

damp concrete surfaces. He recommended routine use of the composite cylinder test for screening epoxy resin compounds for structural concrete applications.

Schutz (Sch 82a) states that the slant shear (composite cylinder) test as specified in ASTM C 882 (ASTM 78d) will eliminate epoxy-resin bonding systems which are affected by bleed water from the plastic concrete and also those systems exhibiting poor bond to concrete.

The slant shear test using rectangular prisms has been reported using either sawn (PaR)* or fractured concrete substrate surfaces (Tab 78). Tabor (Tab 78) advocated fractured surfaces because sawn or cast surfaces of half cylinders or prisms used for various shear tests "do not approximate to the accurately mating irregular surfaces of a typical crack in a piece of concrete." In contrast, Paillere and Rizoulieres (PaR) favored sawn surfaces for several bond test types, including slant shear, because of "the satisfactory reproducibility between laboratories and between test series, whereas with a broken surface it is practically impossible to achieve this," and because research has shown that "this type of surface was more selective and even more representative of product quality."

There have been a number of studies evaluating repair materials which have used the slant shear test (table 3). These include the use of the slant shear test to evaluate the effect of creep in glued joints (Joh 63, Joh 67, Joh 70) and to evaluate the use of underwater repair materials (Bil 79, JSS 82).

The direct shear (shear bond) test has been used in a number of studies to evaluate the shear strength of the bond of a repair material to its concrete substrate (table 3).

Limitations of the direct shear test which can lead to poor reproducibility include (a) sensitivity to eccentric loads (KrN 68, Pac 79) and (b) high stress concentrations (KrN 68). Also, in the direct shear test, if the bond interface is not planar or if it is not perpendicular to the longitudinal axis of the specimen, some unintended repair material or substrate outside of the intended bond plane will be subjected to shear. This condition would be more likely to occur in field-cored specimens. An advantage of the direct shear test is that it can be used for laboratory specimens as well as for field cores (e.g., Spr 84b).

The two studies in table 3, which used the compressive (double) shear type test (Cho 60, Tsu 67), evaluated bonding either hardened concrete to hardened concrete or hardened mortar to hardened mortar. As with the direct shear test, Kriegh and Nordby (KrN 68) state the limitations of sensitivity to eccentric loads and high stress concentrations for the compressive (double) shear test.

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* Date published could not be determined.

Another type of shear test is being considered by the RILEM Committee TC-52 RAC (Resin Adherence to Concrete)* using "push-off" specimens (table 3) for evaluating the "bonding of cured concrete." Several researchers have also used this geometry (ChL 77, ChL 78, Naw 84).

4.2.1.2 Tensile and Flexural Strengths

The tensile bond strength of a repair material to its concrete or mortar substrate has been investigated using a variety of test methods (table 3) including: direct (uniaxial) tension, adhesion ("pull-off"), splitting tension (cylindrical specimens), and "point-load".

Uniaxial tension testing has been used to evaluate the tensile bond strength of repair materials in a number of investigations (table 3).

Long and Murray (LoM 84) and ACI 503R-80 (ACI 80) show how the pull-off test can be used to evaluate the bond between an epoxy mortar or epoxy compound and its concrete substrate. This test, which can be performed in the laboratory or in the field, involves drilling a core through the repair material and partially into its concrete substrate, leaving the core intact in the substrate (see reference LoM 84 or ACI 80). Then a circular probe is bonded to the repair material surface with an epoxy resin having a sufficiently high bond strength so as not to fail during testing (also see reference ACI 80). The probe is then pulled off in a direction normal to the interface, failing (a) the interface, (b) the repair material, (c) the concrete substrate, or (d) a combination of (a), (b), and (c). One preliminary evaluation (Cau 84) of the bond of a number of repair materials to concrete used a commercially available hydraulic jack pull-out instrument. The results indicated that the instrument is useful in evaluating the bond strength of repair materials and that the accuracy could be improved in several ways, including modification of the test instrument. Also, Davey and Boserio (DaB 78) used the pull-off test and presented some data for the bond strength between masonry block wall face shells and its infill grout (high sand content concrete) using a pneumatic apparatus to exert the tensile force.

Fattuhi (Fat 83) has used the splitting tension test with cylindrical laboratory specimens to evaluate the tensile bond strength of repair materials to concrete.

Recently, Saucier used a "point-load" tensile test on field cores to evaluate the tensile strength of the bond between lifts of no-slump, roller-compacted concrete (Sau 84). The plane of the bond interface in the "point-load" test is perpendicular to the longitudinal axis of the cylindrical specimen compared to the splitting tension test, where the interface contains the longitudinal axis of the cylindrical specimen (see table 3 and reference CRD 85). The "point-load" method (CRD 85) is currently being considered for inclusion in the U.S. Army, Corps of Engineers' Handbook of Concrete and Cement.

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* For example, see minutes of committee meeting held in Delft, Netherlands, September 17 and 18, 1984.

Many investigations (table 3) have evaluated the flexural (bending) strength of the bond of a repair material to its concrete substrate.

Few studies have evaluated the feasibility of different test methods to measure the tensile bond strength. In one such study, Fattuhi (Fat 83) used the splitting tension test to evaluate the tensile bond strength of two cured half-cylinders of concrete joined together with a repair material. He also tested concrete beams in flexure in which a groove in the beams was filled with a repair material; the groove was placed on the tension side of the beams. He concluded that the flexure (grooved beam) and splitting tension tests "could be used for evaluating the effectiveness of a repair material in sealing cracks and in transmitting tensile stresses across a crack."

Many of the methods which reputedly measure the tensile strength of plain concrete have the potential to be used to evaluate the tensile strength of the bond of repair materials to concrete. Thus, information on factors affecting the tensile strength of plain concrete may be relevant to evaluating the tensile strength of the repair material's bond to its concrete substrate. Because of this potential relevancy, Hannant's review of test methods to measure the tensile strength of plain concrete (Han 72) is discussed briefly. He discussed the advantages and limitations of the various methods. The methods reviewed were: direct (uniaxial) tension test (over 16 different techniques), splitting tension (cylindrical specimens) test, split cube test, double punch test, ring-tensile test, and the flexure test.

In discussing the direct (uniaxial) tensile strength, Hannant commented that: "The direct tensile test has the advantage that it is the only tensile test in which the tensile stress at failure is known with accuracy and it does not rely on assumptions of elasticity or plasticity in order to calculate this stress."

Other factors noted by Hannant which influence the tensile strength of plain concrete and which may affect the tensile strength of the bond of a repair material to its concrete substrate include: direction of casting, moisture content, fatigue, multi-axial stress systems, the volume of material under stress, and the rate of loading. Another factor indicated by Hannant that needs to be considered in selecting a tensile test method is the application. For example, with a structure subjected to bending, it may be preferable to measure the flexural tensile strength rather than the direct tensile strength.

Hannant concluded from his review:

> "The prediction of the tensile strength of concrete is a complex problem.
>
> The 'true' direct tensile strength of concrete can only be determined reliably by means of a direct tension test and it is now possible to carry out this test in the laboratory with a reasonable degree of confidence.

> Before a concrete mix is designed to resist tensile stresses, the limitations of the various tests which could be used to verify the mix design should be fully understood, otherwise the stress imposed in practice may exceed the limits suggested as a result of the laboratory tests."

4.2.1.3 Volumetric Changes

When a repair material is bonded to its concrete substrate there will always be restraint to a volume change in either the repair material or its substrate. Stresses resulting from this restraint will affect the bond strength. Examples of volume changes causing induced stresses are those which occur (a) during curing, (b) due to temperature changes and differences in the coefficients of thermal expansion of the repair material and its substrate, and (c) due to other environmental effects, such as changes in the moisture content of the repair material or its substrate, or both. Furr (Fur 84) discussed, for different geometries, the role of volumetric changes in inducing stresses for epoxy-resin systems* bonded to concrete:

> "A thin membrane of epoxy bonded to concrete is restrained in the plane of bonding - in two directions. The membrane is free to expand or contract linearly in the third dimension. A pothole filled with an epoxy patching material is restrained in the plane of the pavement, but there is also some restraint in the third dimension because of bonding to concrete around the sides. The patch itself loses heat of curing faster to the cool concrete that it contacts than to the air contacting the third face.
>
> Portions of epoxy used as a crack filler are restrained in three dimensions. If a patch is too bulky, the curing heat loss at its center is slower than at its outer regions, and the dimensional changes in these two regions develop stresses within the patch."

No studies are known to exist on the shrinkage or thermal stresses developed in a material used to repair cracked concrete where the repair material is restrained in three dimensions. There have been, however, studies of overlays on concrete (see sections 4.2.1.3.1 and 4.2.1.3.2).

4.2.1.3.1 Shrinkage

Whitesides (Whi 68) has studied the induced shrinkage stresses caused by curing of epoxy-resin systems. Whitesides defined "effective shrinkage" for an epoxy-resin system as "that portion of the curing shrinkage that occurs after

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* In this report, "epoxy-resin system" refers to a repair material containing an epoxy resin (e.g., epoxy resin adhesives and epoxy resin mortars).

an epoxy system has developed such physical properties that additional shrinkage produces internal stresses in an external environment. In the entity*, the immediate external environment is the bonded face of the concrete and the restraint is limited to the strength of the concrete in shear or in simple tension."

Whitesides (Whi 68) studied the effective shrinkage of epoxy-resin systems (see reference Whi 68 for details) using a photoelastic technique. Using this technique, he investigated the effects of temperature and relative humidity on the internal stresses induced due to the effective shrinkage. He concluded that the "'effective shrinkage' in the epoxy system can produce forces greatly in excess of the ability of portland-cement concrete to contain them." He also suggested a test using an epoxy-glass laminate for determining the effective shrinkage.

Furr (Fur 84) developed equations which can be used to estimate the stresses caused by shrinkage. His equations do not account for the viscoelastic nature of epoxy-resin systems, which will result in some stress relaxation with passing time.

4.2.1.3.2 Thermal Compatibility

Equations for estimating the thermal stresses caused by temperature changes have been developed (Can 67, Fur 84, Spr 82, WFR 83). As in the case of shrinkage, these equations do not take into account the viscoelastic nature of repair materials containing polymers.

Sprinkle (Spr 82) discussed failures caused by temperature changes in thin polymer mortar overlays. He grouped the failures into one or more of three basic types:

1. Formation of vertical cracks through the thickness of the overlay

2. Shearing of portland cement concrete substrate below the bond line

3. Deterioration of the bond between the overlay and its concrete substrate.

He discussed the effects of the properties (e.g., strength) of the overlay and its concrete substrate in relation to each failure type.

The effects of temperature changes are also discussed in the next section.

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* Whitesides referred to the epoxy-resin system bonded to its concrete substrate as an "entity" - see reference Whi 68 for further details.

4.2.2 Effects of Temperature, Moisture, and Loading

A number of studies have evaluated the effects of temperature cycling in air or water on the bond of various repair materials to concrete (GPD 80, GPP 76, GPP 78, Pac 79, SCL 67, Spr 82, Spr 84a, Spr 84b, WFR 83). These studies included (a) the use of polymer mortars or latex-modified mortars bonded to hardened concrete* substrates and, (b) polymer adhesives used to bond fresh mortar to hardened concrete substrates. The minimum and maximum temperatures of the cycles varied, depending on the study. In most cases, 32°F (0°C) was included in the temperature range of the cycles. In most cases, a decrease in bond strength was observed for specimens which had undergone thermal cycling (in some cases moisture was present).

Pace (Pac 79) also investigated the effect of stressing specimens at an early repair age and at various intervals of freezing and thawing and indicated that this stressing "had an adverse effect on the durability of the shear strength of the repaired interface."

A number of laboratory investigations of the effects of moisture on the strength of polymer adhesives, polymer mortars, and polymer-modified mortars have been reported**:

- Ghosh et al. (GSP 69) observed a substantial reduction in compressive strength for polyester resin mortar and epoxy resin mortar specimens resulting from a 7 day immersion in water at 27°C. Inoue (Ino 76), however, reported that some of the epoxy resin mortars tested showed an increase in compressive strength after being immersed in water at 20°C for 2000 h.

- Ohama (Oha 84) showed, for most of the latex-modified mortars studied, that a loss of flexural and compressive strength occurs to some extent due to a 14 day water immersion. Also see reference ACI 77b (page 40 and table 3.12) for additional data.

- The bond strength of epoxy resin mortars to cement mortar generally showed a decrease after the specimens were immersed in water at 20°C for 2000 h (Ino 76).

- Hugenschmidt (Hug 82) investigated cement/mortar prisms with dry surfaces which were bonded using highly cross-linked epoxy resin adhesives. These specimens, which were cured for 7 days at room

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* In reference WFR 83, the bond strength of polymer mortar to a polymer-impregnated concrete substrate was investigated.

** The reader is referred to the references cited for details of the polymers, curing conditions, and control specimens used to determine the effects of moisture.

temperature and then were immersed in water for up to 2 years, showed no loss in flexural strength.

- Ohama's (Oha 84) data showed that the adhesive strengths of several latex-modified mortars to cement mortar were reduced when tested after a 2 day water immersion at 20°C. Also see reference ACI 77b (page 40 and table 3.12) for additional data.

- Mechlenburg et al. (MAE 85), in a screening study of structural adhesives for application to steel bridges, have shown that strength and stiffness in tension for a number of polymer adhesives were reduced significantly when bulk adhesive specimens were exposed to high relative humidities.

Two studies (GPD 80, SCL 67) have evaluated repair materials using (a) accelerated laboratory testing involving temperature or moisture cycling or both, and (b) field performance trials. Both studies investigated the effects of temperature or moisture cycling or both in the laboratory on the shear bond strength of repair materials bonded to concrete substrates. Both studies also qualitatively evaluated the field performance of repair materials used in the laboratory testing. Ghosh et al. (GPD 80) stated that the performance (as measured by bond strength) of the resin mortars which underwent laboratory accelerated testing was qualitatively comparable to the performance of resin mortars used to repair airport runways. (In most cases, Smith et al. (SCL 67) did not state conclusions about the relationship between their accelerated laboratory testing and field performance.)

Several references have treated the evaluation of materials used to repair concrete underwater (Bil 79, Gio 84, JSS 82).

The detrimental effects on the bond strength due to moisture build-up at or near the interface of a repair material and its concrete or mortar substrate have been discussed in references Ino 76, Pac 79, RoS 69, Sch 80, Sch 82b, SCL 67 and War 84. (Here "detrimental effects on the bond strength" includes deterioration of the concrete substrate as well as deterioration of the bond of the repair material to its concrete substrate.) References Pac 79, Sch 80, Sch 82b, SCL 67, and War 84 discuss the detrimental effects on the bond strength of water build-up combined with freeze-thaw cycles. For example, for epoxy-resin systems applied to concrete on grade, Schutz (Sch 82b, Sch 86) indicated that conditions which cause a moisture build-up near the bond line can result in deterioration and loss of bond between the epoxy-resin system and its concrete substrate. According to Schutz, this deterioration and loss of bond can occur:

(1) prior to cure, when one or more of the following occur: (a) air or water vapor causes blisters in the epoxy-resin system, (b) these blisters erupt and cause "volcanos" (small eruptions), or (c) the epoxy-resin system cures on a layer of condensed water vapor which acts as a bond breaker.

(2) after cure, in a non-frost resistant concrete substrate, when moisture build-up exceeding the critical saturation point (of the concrete substrate) occurs in combination with freeze-thaw cycling.

There is little information in the literature on the performance of an impermeable repair material layer applied to frost resistant concrete and there is varied opinion (e.g., see Sch 80) about the durability of such a repair when exposed to freeze-thaw cycling in the presence of moisture. In freeze-thaw testing, the adverse effects of volumetric changes due to differences in the thermal coefficients of expansion need to be considered.

There have been many studies on the effects of the load duration or the temperature during loading or both on the strength, stiffness, and deformation of polymer adhesives, polymer mortars, and polymer concretes (materials containing polymers evaluated with their concrete substrates: Fat 83, Hug 76, Hug 82, Joh 63, Joh 67, Joh 70; and materials containing polymers evaluated without a concrete substrate: AyD 81, AyD 84, BHG 70, Hri 81, Hug 76, Hug 82, KoI 76, OKY 76, Sta 76, VaN 76). These studies related to load duration or temperature during loading or both generally support the following conclusions about trends which can cause structural or serviceability failures in polymer adhesives, polymer mortars, and polymer concretes:

- Increasing the fraction of sustained load (measured as a percentage of the ultimate short term load) or the duration of loading or both, causes an increase in the amount of creep deformation*.

- Increasing the testing temperature generally causes a decrease in strength and stiffness and an increase in creep deformation. In some of the studies, very large decreases in strength and stiffness (e.g., BHG 70, Joh 70, KoI 76) and very large increases in creep deformation (e.g., OKY 76) occurred with increasing testing temperature. This behavior (very large changes in properties) is most likely caused by the proximity of the testing temperature to the glass transition temperature** of the polymer studied.

For information on the creep characteristics, including the effects of temperature, load duration, and fraction of sustained load, the reader is referred to references ACI 77b, AyD 81, AyD 84, Hug 76, Hug 82, Joh 63, Joh 67, Joh 70, OKY 76, and Sta 76.

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* Creep deformation was measured in either strain or strain per unit stress.

** For example, see Eisenhut's references (Eis 85a, Eis 85b) which discuss the viscoelastic behavior of polymers and the significance of the glass transition temperature in relation to the performance of polymer adhesives used in "structural" uses (adhesive transmits or distributes loads) and "non-structural" uses. Also see reference ACI 77b for a discussion of the viscoelastic behavior of polymer mortars and concretes.

From studies of loading duration, temperature during loading, and fire tests(see references Lev 82 and SuS 76 for fire tests), the following important conclusions can be drawn for polymer adhesives, polymer mortars, and polymer concretes:

1. Short term tests are not reliable indicators of long term performance.

2. Tests conducted at one temperature (typically room temperature) do not provide information on the performance at other temperatures.

3. There can be a wide range in the viscoelastic* behavior for a given polymer type (e.g., epoxy resins).

4. Special tests are needed to evaluate the effects of fire or high temperatures or both on structural performance, smoke evolution, and gas evolution.

With regard to the strength and deformation characteristics of polymer mortars and concretes (PC), reference ACI 77b states:

> "Most strength and deformation data for PC have been determined from strength tests of short duration and creep tests at stress levels below the long-term strength. The resulting stress-strain relationships do not reflect the magnitude of the viscous deformations which might occur under service loadings, and the reduced strength associated with extended durations of loading. Further, the effects of environments other than laboratory conditions on the response of PC to mechanical stress have not been studied in detail."

There have been a number of studies (ChL 77, ChL 78, CSP 84, MaO 85, PoB 75) of the repair of cracks or joints in either plain or reinforced concrete members using epoxy-resin systems (epoxy injection, etc.). These studies compared the performance of the original (see references) specimens with their performance after the repair had been made. With several exceptions, the performance of the repairs were determined to be effective. The specimens in these studies were apparently tested at or near room temperature and under short term loading. Hence, neither the effects of temperature (e.g., high temperature) nor sustained loading on the performance of the repairs were evaluated in these studies.

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* For example, see Eisenhut's references (Eis 85a, Eis 85b) which discuss the viscoelastic behavior of polymers and the significance of the glass transition temperature in relation to the performance of polymer adhesives used in "structural" uses (adhesive transmits or distributes loads) and "non-structural" uses. Also see reference ACI 77b for a discussion of the viscoelastic behavior of polymer mortars and concretes.

Ohama (Oha 84) presented data and information on temperature effects, including the influence of the glass transition temperature on the strength of polymer-modified mortars and concretes. Ohama's flexural strength data (Oha 84), showed that, with increasing temperature, strength reductions occurred in the polymer-modified mortars investigated. It is noted that reference ACI 77b also contains information on the effects of temperature on latex-modified concrete.

Ohama (Oha 84) stated that conflicting data exist on the creep behavior of latex-modified mortar and concrete. Research (Oha 84) has indicated that two types of latex-modified concrete exhibited considerably lower creep strain levels as compared to unmodified concrete. Other research (Sol 67) cited in reference Oha 84, however, found that creep deformation in flexure for one type of polymer-modified mortar was "several times larger than that of unmodified concrete at 20°C, and its catastrophic deformation occurred at 50°C since the polymer developed a high plasticity above its glass transition temperature" (Oha 84).

Mangat et al. (MBE 81) investigated the creep characteristics of polymer-modified concretes under uniaxial compression. For the concretes and test conditions studied they state: "The results indicate that the acrylic based polymers generally lead to higher creep strains relative to plain concrete. The styrene-butadiene polymer, on the other hand, leads to a reduction in creep."

Ohama et al. (OSI 81) have presented data on the incombustibility of polymer-modified mortars. Many of the mortars, when evaluated according to JIS A 1321 (Testing Method for Incombustibility of Internal Finish Material and Procedure of Buildings), had "good incombustibility" (OSI 81). The authors discuss the effects of polymer type, polymer-cement ratio, and polymer content on the incombustibility of the polymer-modified mortars studied.

Ohama (Oha 84) investigated the durability of latex-modified mortars in terms of their adhesion in flexure to ordinary cement mortar under 10 years of outdoor exposure in Tokyo. He stated: "In contrast to unmodified mortar-bonded specimens which failed within one-year outdoor, most latex-modified mortar-bonded specimens had a satisfactory adhesion for practical use after the 10-year exposure period."

4.2.3 Standards and Specifications and Bond-Related Test Methods

Current ASTM standard specifications and their bond-related standard test methods for concrete repair materials are given in table 3. Some examples of other standards and specifications requiring bond-related tests for concrete repair materials containing polymers are also shown. Although the information in table 3 does not cover all standards and specifications world-wide, it does indicate that a variety of bond-related tests (required by standards and specifications) are in existence. In addition to the information given in

table 3, there are a number of references* (Deg 84, FIP 78, OMK 76, SaF 83, and TiL 84) which either propose or discuss a variety of bond-related tests (e.g., tension, shear, flexure,and thermal compatibility). Thus, it is evident that a number of bond-related tests, in addition to the ASTM bond-related standard test methods (table 3), are either in existing standards and specifications or are being proposed or considered for evaluating the bond strength of repair materials containing polymers.

Many of the bond-related tests referenced by the standards and specifications in table 3 apply only to epoxy-resin systems. Furr (Fur 84) has discussed the ASTM, AASHTO, and ACI specifications, as well as several U.S. state highway department specifications, for epoxy materials used with concrete.

The ASTM bond-related standard test methods (see table 3 for ASTM reference citations) for evaluating concrete repair materials are for epoxy-resin systems (C 882, C 883 and C 884) and latex systems (C 1042). Of these test methods only the slant shear test method (C 882 and C 1042) is quantitative.

The ASTM C 884 thermal compatibility test method, which involves thermal cycling, is qualitative. In contrast, the thermal cycling test in reference HRS 78 is quantitative, requiring adhesion (pull-off) tensile testing of the bond strength after completion of the thermal cycling. (Details of the thermal cycling and the bond strength criteria are given in reference HRS 78.)

The ASTM C 883 effective shrinkage standard test method involves constructing a laminate consisting of an epoxy-resin system applied to a glass plate. As the epoxy cures, any shrinkage of the epoxy will cause bowing of the glass plate. The test is also qualitative, with failure defined as sufficient shrinkage to cause the glass plate to fracture.

4.2.4 Properties and Test Methods for Plain Repair Materials

Pertinent ASTM test methods for (a) polymers and plastics,and (b) portland cement concrete and mortar have the potential for evaluating the physical, mechanical, and chemical properties (table 4) related to the performance of plain repair materials. Plain repair materials include polymer adhesives, polymer mortars and concretes, and polymer-modified mortars and concretes without their concrete substrates.

The test methods to determine the pertinent properties of plain repair materials are not treated in detail. (Some properties of plain repair materials, however, are discussed in the next section.)

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* Also see minutes of RILEM Committee TC-52 RAC Resin Adherence to Concrete - for example, see minutes of meetings held in Athens, Greece, April 12 and 13, 1984 and in Delft, Netherlands, September 17 and 18, 1984.

4.3 Factors Affecting Performance of Repair Materials

Table 4 lists the performance requirements, degradation factors, and properties related to performance for polymer adhesives, polymer mortars and concretes, and polymer-modified mortars and concretes used to repair concrete. Table 4 is based on numerous references (e.g., ACI 77b, ASTM 82, Bil 79, Bul 80, DeP 81, FIP 78, Fur 84, ISO 84, Sca 84, Sch 80, Sch 82a, Sch 82b, War 84, Whi 68, and the standards and specifications given in table 3). Although the information in table 4 covers many situations, it is not comprehensive. Therefore, each structure to be repaired needs to be carefully analyzed on an individual basis, choosing the appropriate performance requirements, degradation factors, and properties related to performance from table 4 and adding any performance requirements, degradation factors, and properties related to performance as encountered or needed. The properties related to performance are considered preliminary because their relationship to in-service performance needs to be established.

Based on research references, standards, and specifications, a summary of the more important factors affecting performance is given. A statement of research needs related to developing performance tests and criteria is also included. The information in the summary and information derived from additional research are considered a first step in the process of developing performance criteria and are intended to serve as a guide in selecting performance requirements, degradation factors, properties related to performance, and relevant existing test methods and their parameters. The repair materials covered are polymer adhesives, polymer mortars and concretes, and polymer-modified mortars and concretes which can be used to overlay or repair portland cement concrete in different types of concrete structures and their varying environments.

4.3.1 Summary

1. The most important performance requirements are considered to be (a) the ability of a repair material to bond to its concrete substrate, and (b) for the repair material, its concrete substrate*, and the bond of the repair material to its concrete substrate* to withstand all in-service stresses and strains under the in-service degradation factors (loading, temperature, moisture, etc.) for the intended life of the repair. The tests associated with these performance requirements can be classified into tests that simulate externally applied stresses and strains and those that simulate internally induced stresses and strains.

* The performance requirements of the repair material as related to its concrete substrate are that the repair material must not cause its concrete substrate to fail.

Test Methods Simulating Externally Applied Stresses and Strains

Because of its simplicity and reputedly good precision* (repeatability), the ASTM slant shear standard test methods (C 882 (ASTM 78d) and C 1042 (ASTM 85)) appear to be excellent screening tests for evaluating the strength of epoxy-resin bonding systems (C 882) and latex bonding systems (C 1042) used with portland cement concrete or mortar. The slant shear test also has the potential for evaluating repair materials not covered by ASTM C 882 and C 1042, including (1) polymer systems other than epoxy-resin and latex bonding systems, and (2) overlay materials, such as polymer-modified concrete, where the overlay material would comprise one-half of the slant shear specimen.

In addition to the slant shear test, other bond tests (table 3), such as tension, shear (direct or "other"), and flexure are important and need to be considered because:

(a) in some cases, they better reflect the stress state in the structure being repaired (e.g., use of flexure test for an in-service pavement in which the repaired pavement portion is subjected to flexural stress),

(b) some of these tests have been used extensively in research investigations to measure bond strength (table 3),

(c) some of these tests are being used, or are being proposed or considered for use, as standard test methods (see section 4.2.3), and

(d) these bond tests can provide information on the strength properties (tensile, shear, etc.) of the plain repair material as well as its bond strength to its concrete substrate.

The bond strength tests should incorporate degradation factors which simulate the expected in-service conditions, including temperature and moisture conditions. Depending on the nature of the repair, more than one type of bond test may need to be used when evaluating repair materials.

Creep related properties (e.g., strength, stiffness, and deformation) are important for repair materials, such as polymer adhesives, polymer mortars, and polymer concretes, which may deform excessively under sustained loading or high temperature or both. When appropriate, creep tests should be considered, including those which measure (1) the creep of the plain repair material, and (2) the creep of the interface of the repair material at its concrete substrate, such as when hardened concrete is bonded to hardened concrete with a repair material. The appropriate stress state (e.g., tension, compression, or shear) and other degradation factors, particularly temperature and moisture, need to be chosen for the creep tests. Also the appropriate magnitude of the load applied (fraction of short-term ultimate load) and the load duration, either short or long term, would need to be determined.

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* See memo of ASTM Committee C-9 dated June 19, 1985 showing round robin test results based on ASTM C 882.

Test Methods Simulating Internally Induced Stresses and Strains

Volumetric changes of the repair material relative to its concrete substrate (or the concrete substrate relative to the repair material) result in internally induced stresses. Volumetric changes include those (a) caused by temperature or moisture content changes or both in the repair material relative to its substrate (or changes in the substrate relative to the repair material), and (b) occurring during curing of the repair material (e.g., shrinkage).

The ASTM C 884 thermal compatibility standard test method (ASTM 78e) provides information on the effects of thermal cycling in air for an epoxy-resin sand mortar overlay on a concrete substrate. The test, however, does not:

- incorporate the effects of moisture as an agent causing relative volumetric changes or other degradation, or causing freeze-thaw degradation (see 2. below),

- provide a quantitative measure of the degradation caused by the test conditions, and

- provide an indication if the induced cracking or delamination is limited to the slab edges or has also occurred in portions closer to the slab center.

The tensile pull-off test (table 3) offers the potential to be used in conjunction with ASTM C 884 to quantitatively measure the degradation of the bond strength occurring during thermal cycling and to determine the bond strength both near the slab edges and closer to the slab center. Reference HRS 78 requires tensile pull-off testing after the slab has been thermally cycled in water, salt water, and air.

The ASTM effective shrinkage test method (ASTM C 883 (ASTM ᶠ0b)), while providing information on the effects of shrinkage of an epoxy-resin system on a glass plate, does not provide a quantitative measure of shrinkage nor a measure of the shrinkage of the epoxy-resin system relative to its concrete substrate.

2. Temperature and moisture conditions, imposed either before or during application or inducement of stress and strain, are also considered important degradation factors to be incorporated in test methods.

Important properties* related to the performance of repair materials subjected to the effects of temperature and moisture include:

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* Properties related to the concrete substrate are given when the repair material can cause its concrete substrate to fail.

(i) resistance of the repair material, its concrete substrate, and the bond of the repair material to its concrete substrate to volumetric changes resulting from:

- temperature changes (e.g., thermal cycling) - caused by differences in the coefficient of thermal expansion of the repair material and its concrete substrate (also see 1. above).

- changes in moisture content (e.g., wetting and drying cycles) of the repair material and its concrete substrate (also see 1. above).

The modulus of elasticity, strain at ultimate stress, and viscoelastic properties (e.g., relaxation) of the repair material are also important in accomodating the volumetric changes which occur between a repair material and its concrete substrate.

(ii) liquid water absorption, and the liquid water or water vapor transmission rates through the repair material and along the interface of the repair material with its concrete substrate

(iii) resistance to freezing and thawing of the repair material, its concrete substrate, and the bond of the repair material to its concrete substrate

(iv) resistance to degradation of the repair material, its concrete substrate, and the bond of the repair material to its concrete substrate when exposed to liquid water or water vapor. Included are the effects of a moisture build-up at or near the bond interface or in the concrete substrate. Examples include: (a) application of a low permeability repair material on a permeable, non-frost resistant concrete substrate resulting in a water build-up in the substrate and increased susceptibility to freeze-thaw damage to the concrete substrate, (b) repair material curing on a layer of condensed water which acts as a bond breaker, and (c) possible degradation of the mechanical properties of the polymer in the presence of moisture.

(v) resistance to excessive deformation - e.g., excessive deformation caused by stress being applied at a temperature sufficiently close to the glass transition temperature of the polymer in the repair material.

Temperature and moisture conditions which simulate the in-service conditions should be used when determining the above properties.

3. Other factors related to performance which need to be considered are:

(a) While the performance requirements, degradation factors, properties related to performance, and associated tests given in this section (4.3.1) are considered the most important, it is still

necessary to consider all pertinent performance requirements, degradation factors, properties related to performance, and associated test methods when developing performance tests and criteria (see table 4).

(b) The actual dimensions of the in-service repair relative to the dimensions of the test specimen need to be considered. Examples include: (a) volume of repair material used in the in-service repair could generate excessive heat resulting in degradation of properties as compared to a much smaller volume used in a test specimen, where little heat is generated, (b) if a degradation process requires moisture and is controlled by diffusion, then the diffusion of moisture and the corresponding degradation in an in-service repair may differ from that occurring in a small-dimensioned test specimen, (c) similarly, if a degradation process is controlled by temperature, the temperature distribution in the in-service repair may differ from that occurring in a small-dimensioned test specimen, and (d) the dimensions of the repair used in service may differ from those used in a test specimen, which could result in different stress and strain levels in the in-service repair as compared to the test specimen.

(c) The surface and near surface characteristics of the concrete substrate of the test specimen on which the repair material is applied can significantly affect the bond and should simulate as closely as possible the in-service conditions. Surface and near surface characteristics of the concrete substrate which can affect the bond include: moisture, temperature, contaminants, texture and roughness, strength, freeze-thaw resistance, and the ratio of cement paste to aggregate.

4. Existing ASTM standard specifications and their bond-related standard test methods for concrete repairs with epoxy-resin systems and latex agents and systems (table 3) are useful in developing performance tests and criteria for repair materials because the standard specifications and their standard test methods:

(a) can serve as interim performance criteria for the epoxy-resin systems and latex agents and systems covered until more relevant performance criteria are developed,

(b) reflect, at least to some degree, the in-service performance of the epoxy-resin systems and latex agents and systems covered,

(c) have the potential to be modified to include repair materials other than the epoxy-resin systems and latex agents and systems covered, and

(d) have the potential to be modified to reflect in-service conditions (temperature, moisture, stress state, etc.), degradation mechanisms, and performance.

However, the existing ASTM standard specifications and their standard test methods may not adequately simulate in-service conditions, degradation mechanisms, and performance because:

- the test conditions may not be closely related to the expected in-service conditions (see 1., 2., and 3. above), and

- the test methods have not been systematically related to in-service performance.

ASTM test methods that have the potential to be used to measure the important properties of plain repair materials (without their concrete substrates), including those properties related to temperature, moisture, and strength, were not covered in this report. It would appear, however, that pertinent ASTM test methods for (a) polymers and plastics, and (b) portland cement concrete and mortar have the potential to be used or modified to measure the properties of plain repair materials. (Also see section 4.2.4.)

4.3.2 Research Needs

Consideration should be given to the following research needs:

1. The in-service conditions of the structure being repaired should be quantified. If possible, the characteristics (e.g., amplitude, rate*, frequency, number, duration, and sequence) of the cycles of degradation factors (stress, strain, temperature, moisture, etc.) that the structure experiences should be quantified.

   Environmental conditions (loading, temperature, etc.) could be represented by several "standard" environments, with each "standard" environment representing the environment in structures subjected to similar environmental conditions.

2. The degradation mechanisms occurring in service for different types of repair materials and their concrete substrates should be identified and quantified. Quantitative degradation indicators (e.g., bond strength) need to be identified which will define the degree of degradation and final failure. The degradation factors of temperature and moisture need special consideration, including their possible synergistic effects.

3. Simple and rapid screening tests which simulate in-service conditions, degradation mechanisms, and performance, should be developed, possibly including pilot tests which simulate the degradation factors and other in-service factors (e.g., geometry) of the structure being repaired. For example, in an evaluation of underwater repair

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* "Rate" refers to the rate at which a degradation factor is occurring within a given cycle - e.g., rate of applying load.

materials (Bil 79), it was discovered using screening tests, that some repair materials, which appeared to be effective based on preliminary small-scale tests, were not effective based on larger-scale trials.

Tests which can be performed both in the laboratory and in the field should be considered - they would be helpful in establishing the relationships between laboratory test results and in-service performance.

4. Analytical modeling of repair materials bonded to their concrete substrates to determine the relative importance of the factors affecting in-service performance should be conducted (see section 4.3, including table 4). For example, the effects of small-scale specimen size and geometry on the stress and temperature distributions and the movement of moisture at or near the interface of the repair material and its concrete substrate could be studied. The results for small scale specimens could be compared with results for repair materials applied to full-scale, in-service concrete structures.

5. Consideration should be given to investigating if the "time-temperature superposition" technique is applicable for repair materials containing polymers, such as polymer adhesives, polymer mortars, and polymer concretes. If the technique is applicable, information based on short-term experiments conducted at different temperatures could be used to estimate long term behavior (e.g., creep - see references Fer 70 and Hri 81).

6. The information in this section (4.3), together with ASTM E 632 (ASTM 82), should be used as a guide in:

   (a) modifying existing tests (e.g., ASTM) or developing new performance tests to quantitatively simulate the in-service conditions, degradation mechanisms, and performance of polymer adhesives, polymer mortars and concretes, and polymer-modified mortars and concretes currently used as concrete repair materials,

   (b) systematically and quantitatively establishing the relationships of the results of the performance tests (modified or newly developed in (a) above) to in-service performance, and

   (c) establishing performance criteria based on the performance tests and the relationships of their results to in-service performance.

   The order of importance of the properties which are related to in-service performance should be established when modifying or developing performance tests.

Care should be taken to insure that any accelerated testing simulates the in-service conditions, degradation mechanisms, and performance.

5. SUMMARY AND APPLICATION OF FINDINGS

This chapter summarizes the more important findings and indicates how these findings can be used in the process of developing performance tests and criteria.

This report provides the status of information related to the performance of materials containing polymers used to repair portland cement concrete, including performance requirements, degradation factors, properties related to performance, and pertinent existing test methods and their parameters. Research needs related to developing performance tests and criteria are also given. The following types of repair materials which contain polymers were covered: sealant type materials for repairing active cracks, and polymer adhesives, polymer mortars and concretes, and polymer-modified mortars and concretes for repairing spalls and dormant cracks and for placing overlays.

This report is intended to be the first step in the process of developing performance tests and criteria for materials to repair concrete. The information in it can be used as a guide in identifying and selecting (1) the important performance requirements, degradation factors, and properties related to performance, and (2) pertinent existing test methods and their parameters to measure the properties related to performance. (Summaries of the factors affecting performance are given in section 3.3 for sealant type materials used to repair active cracks and in section 4.3 for materials containing polymers used to repair spalls and dormant cracks and to place overlays.)

Much research is needed with respect to the details of developing performance tests and criteria. These details are not easily determined because of gaps in existing knowledge and the associated research needs including:

(a) Although information in the literature was used to identify important degradation factors (e.g., loading, movement, temperature, moisture, etc.), the characteristics (magnitude, frequency, etc.) of the degradation factors used in laboratory testing cannot be accurately established until the in-service environmental conditions (loading, movement, temperature, moisture, etc.) of the structure to be repaired are known. One approach would be to establish several "standard" environments, with each "standard" environment representing the environment in structures subjected to similar environmental conditions.

(b) A lack of information exists on the relationships of laboratory test results to in-service performance. The in-service degradation mechanisms should be identified and quantified. Quantitative performance tests, which simulate in-service conditions, degradation mechanisms, and performance, should be developed (or modified -

see (c) below) and the results of these performance tests should be systematically and quantitatively related to in-service performance.

Consideration should be given to developing tests which can be performed both in the laboratory and in the field - they would be helpful in establishing the relationships between laboratory test results and in-service performance. Analytical modeling of the behavior of the repair materials bonded to their concrete substrates should also be considered. This modeling may be helpful in establishing the relative importance of the factors affecting in-service performance, including degradation factors (stress, strain, temperature, moisture, etc.) and other effects, such as size and geometrical differences between laboratory specimens and in-service repair installations.

The development of screening tests should be considered which would simulate in-service conditions, degradation mechanisms, and performance, yet could be conducted relatively easily and rapidly.

Performance criteria should be established based on (1) the modified or developed performance tests (including screening tests, if appropriate), and (2) the relationships of the performance test results to in-service performance.

(c) The current ASTM and Federal standards and specifications and their test methods for the repair materials covered may not adequately simulate the in-service conditions, degradation mechanisms, and performance of the repair materials. The relationships of these standards and specifications and their test methods to in-service performance should be established (see (b) above).

It may be possible to modify the ASTM and Federal standards and specifications and their test methods to quantitatively simulate the in-service conditions, degradation mechanisms, and performance of (1) repair materials currently covered, and (2) related repair materials currently not covered.

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Table 1A

Federal Specifications for Joint Sealants for Concrete

No.	Scope[a]	Maximum Total Joint Movement[b]
TT-S-001657 (FED 70c)	Single component, solvent release type, butyl rubber based sealing compound for sealing, calking, and glazing operations in buildings and other types of construction.	10 percent for Type I and for Type II *
TT-S-00230C (FED 70b)	Single component, cold-applied elastomeric type joint sealing compound (joint sealant) for sealing, calking, and glazing operations in buildings, building areas (plazas, decks, pavements, etc.), and other types of construction.	50 percent for Class A (includes Type I and Type II) 25 percent for Class B (includes Type I and Type II)
TT-S-00227E (FED 69)	Multi-component cold-applied elastomeric type joint sealing compound (joint sealant), including curing agents, for sealing, calking, and glazing operations in buildings, building areas (plazas, decks, pavements, etc.), and other types of construction.	50 percent for Class A (includes Type I and Type II) 25 percent for Class B (includes Type I and Type II)
TT-S-001543A (FED 71)	Single component cold-applied silicone rubber base joint sealing compound (joint sealant) for sealing, calking, and glazing operations in buildings, building areas, and other types of construction. Sealant ... shall not be used in sealing joints in horizontal decks, plazas, patios, driveways, terraces and other areas where foot traffic and mechancial abuse are encountered. The sealant shall not be used in submerged joints such as in fountains, reflecting, and swimming pools.	50 percent for Class A 25 percent for Class B
SS-S-200E (FED 84a)	Two types of two-component, elastomeric, cold-applied, jet-fuel-and jet-blast-resistant sealing compounds for use in sealing joints and cracks in portland cement concrete pavement.	
SS-S-1401C (FED 84b)	One type of one-component, hot-applied material for use in sealing joints and cracks in portland cement and asphalt concrete pavements.	
SS-S-1614A (FED 84c)	Two types and two classes of one-component, jet-fuel-resistant, hot-applied material for use in sealing joints and cracks in portland cement and tar concrete pavements.	

[a] Taken from specifications - see specifications for additional details on use and precautions.

[b] See specifications for definitions and explanations of "maximum total joint movement," "type," and "class." Also see specifications with regard to testing requirements involving bond, extension, compression, etc. Note that, according to J. Panek (private communication, June, 1986), the "maximum total joint movement" as defined and explained in the Federal specifications is not consistent with the latest methods of expressing movement capability and can lead to misinterpretation and improper joint design. For further clarification, see sections 2.3 and 5.1 of reference PaC 84. Also see reference PaC 84 for estimates of movement capability for some generic sealant types.

Additional note: The reader is also referred to the relevant federal specifications and related information in the latest edition of "Index of Federal Specifications, Standards and Commercial Item Descriptions," General Services Administration, Office of Federal Supply and Services.

Table 1B

ASTM Standard Specifications for Joint Sealants for Concrete

No.	Scope[a]	Joint Movement[b]
C 834-76 (ASTM 76b)	One-component latex sealing compound for use as a caulking compound or sealant in building construction.	Compounds generally formulated to withstand a maximum total joint movement of 15% (± 7.5% in extension and compression) of the nominal joint width.
C 920-79 (ASTM 79)	Cured single-or multicomponent cold-applied elastomeric joint sealant for sealing, caulking, or glazing operations on buildings, plazas, and decks for vehicular or pedestrian use, and types of construction other than highway and airfield pavements and bridges.	Class 25 - A sealant that when tested ... shall withstand an increase and decrease of at least 25% of the joint width ... Class 12-1/2 - A sealant that when tested ... shall withstand an increase and decrease of at least 12-1/2% of the joint width ...
D 1850-74 (ASTM 74b)	Concrete joint sealer of the cold-application, mastic, single or multiple-component type, intended for use in sealing joints having a minimum width of about 1/2 in. (13 mm) in concrete pavements, bridges, and other structures.	
D 1854-74 (ASTM 74a)	Jet-fuel-resistant concrete joint sealer, of the hot-poured elastic type, intended for use in sealing joints in concrete pavement in areas exposed to jet fuel spillage and the blast from jet airplane engines. It may be found useful in industrial areas where similar conditions exist.	
D 1190-74 (ASTM 74c)	Concrete joint sealer of the hot-poured elastic type, intended for use in sealing joints in concrete pavements, bridges, and other structures.	
D 3405-78 (ASTM 78a)	Joint sealants of the hot-poured type intended for use in sealing joints and cracks in portland cement concrete and asphaltic concrete pavements.	
D 3406-78 (ASTM 78b)	Elastomeric type of one-component, hot-applied, concrete joint sealant highly resistant to weathering for use in sealing joints and cracks in portland cement concrete highway and airfield pavements.	
D 3569-76T (ASTM 76a)	Elastomeric type of one-component, hot-applied, jet-fuel-resistant, concrete joint sealant highly resistant to weathering for use in sealing joints and cracks in portland cement concrete airfield pavements in critical areas subject to jet-fuel spillage and jet blast.	
D 3581-80 (ASTM 80a)	One type of thermoplastic, hot-applied, jet-fuel-resistant joint sealant for use in sealing joints and cracks in pavements (portland cement concrete and tar-concrete pavements).	

[a] Taken from specifications; see specifications for definitions of types, grades, classes, and also for additional details on use, application, and precautions.

[b] Taken from specifications - see specifications for further detail. Also see specifications and their references with regard to testing requirements involving bond, extension, recompression, etc. Also see reference PaC 84 for estimates of movement capability for some generic sealant types.

Table 2[a]

Performance Requirements, Degradation Factors, and Properties Related to Performance of Sealant Materials Used to Seal Active Cracks

Performance Requirements and Associated Degradation Factors[b]		Properties[b,c] Related to Performance
1. Accomodate the amplitude, rate[d], number, *frequency*, *duration*, and sequence of strain and stress cycles[d] occurring under service conditions, including cycles caused by: changes in temperature or moisture content or both of concrete, drying shrinkage of concrete, chemical reactions (e.g., sulphate, alkali-aggregate) in concrete, movement-induced (e.g., settlement) strain and stress in concrete, vibration-induced strain and stress in concrete, creep of concrete, volumetric changes of sealant material during its cure, and applied loads (e.g., dead and live). Including:		
(i) Not internally rupture (*not fail in cohesion*) and must remain in contact (bond) with joint faces (not fail in adhesion, nor peel at corners or other local areas of stress concentration). Not fail by brittle fracture or by tearing.	1.(i)	Resistance of sealant and its bond to its concrete substrate to one or more cycles[d] of strain and stress (e.g., tension (extension), compression (also recompression), shear, bond (adhesion and tenacity), peel, bending, impact, shrinkage, and combinations of these (tension and shear, etc.)). Resistance to tearing. Resistance to brittle fracture. Movement capability, curing shrinkage, and modulus of elasticity. Properties related to *tensile testing* (*see sections* 3.2.1 *and* 3.2.2).
(ii) *Sufficiently recover its original properties* and shape after one or more strain and stress cycles, including resistance to compression set (e.g., compression deformation for a specified duration and at an elevated temperature). Will not extrude (be squeezed) out of joint.	1.(ii)	Elasticity, permanent set (including tension and compression), resilience, stress relaxation, creep, and recovery.
(iii) Sealant not to cause concrete substrate to fail (e.g., in tension or shear) - caused by sealant stress exceeding concrete strength.	1.(iii)	Same as 1.(i) with the additional need to evaluate the sealant properties as they would cause a failure in the concrete substrate.
2. Resist flow[e] or rupture or both due to gravity, fluid pressure, and high temperature; resist sagging or unacceptable softening or both at high temperatures. Not harden or become unacceptably brittle at low temperatures.	2.	Creep deformation, creep rupture, and hardness. Resistance to fluid pressure[f], penetration, flow[e], rupture, slump, sag, and unacceptable softening at elevated temperatures. Resistance to unacceptable brittleness or hardening at low temperatures.
3. Prevent passage of any unwanted substances (gases, liquids, and solids) including wind, water, dust, dirt, insects, etc. The unwanted substances can be under pressure. Sealant and sealant bond must protect the concrete *substrate against damage* (e.g., *freeze-thaw*).	3.	Permeability. Resistance to absorption *and infiltration of any* unwanted substances (also see 4. and 5.).
4. Be impermeable to, and resist effects of, moisture including water immersion, splash, wetting and drying, freezing and thawing, rain, hail, humidity, condensation, snow, ice, and liquid pressure gradients.	4.	Permeability, water absorption, resistance to moisture degradation, and resistance to temperature cycling in the presence of *moisture*, including freeze-thaw cycling.

(Continued)

Table 2 (Continued)

Performance Requirements and Associated Degradation Factors[b]	Properties[b,c] Related to Performance
5. Resist intrusion, infiltration, embedment, and penetration of foreign material (compressible and incompressible[g] -also see 3. and 4.) including: fluids, ice, dust, dirt, gravel, sand, debris, vegetation, insects, and animals. Resist abrasion, wear, indentation, and pick-up, including that due to human or vehicular traffic. Resist attack by animals, insects or humans.	5. Hardness, resilience, and recovery. Resistance to penetration, infiltration, intrusion, embedment, and indentation (also see 3. and 4.). Abrasion resistance. Wear resistance. Resistance to pickup.
6. Not adversely affected by aging, weathering, and other service factors under the range of service conditions, including: temperature extremes (e.g., freezing or direct heat of aircraft engines), moisture (see 4.), ultraviolet (UV) light, wind, normal air constituents (e.g., ozone), and air contaminants. Resist formation of toxic gases or smoke or both (e.g., fire or high temperature exposure). Resist chemical attack (gases, solids, liquids (e.g., solvents, acids, oils, fuels, and sulfate or salt solutions)) and biological attack (e.g., by bacteria).	6. Hardness. Resistance to accelerated, artificial, and natural weathering, aging, heat aging, UV light, wind, normal air constituents (e.g., ozone), air contaminants, moisture (see 4.), biological environments, chemicals (including immersion in fuels, solvents, etc.), temperature extremes, fire (including toxic gas or smoke formation or both), and other service factors. Resistance to environmental, chemical, and other treatments - can also be performed prior to or during testing of the properties in this table. Resistance to loss of adhesion, loss of cohesion, loss of tenacity, tearing, chalking, crazing, checking, blistering, swelling, separating, opening, delaminating, weight loss, embrittlement, cracking, bubble or internal void formation, hardening, tackiness, flow[e], and unacceptable softening. Resistance to change in weight or mass, volume change at elevated temperature, formation of an oil-like film or reversion to a mastic-like substance, and loss of resilient rubber-like properties. Solubility (e.g., in fuel).
7. Meets all the appropriate requirements in this table prior to and during curing of sealant. Also resist blistering and bubbling prior to and during curing.	7. Resistance to any adverse effects occurring prior to and during curing of sealant, including adverse effects caused by strain and stress cycles[d], sealant shrinkage, and any other appropriate properties in this table. Also resistance to blistering and bubbling prior to and during curing.
8. Resist staining or color change.	8. Resistance to staining or color change.

[a] Although the information in this table covers many situations, it is not comprehensive. Therefore, each structure to be repaired needs to be carefully analyzed on an individual basis, choosing combinations of the appropriate entries of performance requirements, degradation factors, and properties related to performance from this table and adding any performance requirements, degradation factors, and properties related to performance as encountered or needed. The sources used in the preparation of this table (e.g., ACI 77a, AFM 83, ASTM 82, Bee 80a, ISO 75, ISO 84, PaC 84, and the Federal and ASTM standards and specifications listed in table 1) contain further details, including performance-related information and functions of joints.

[b] Performance requirements, degradation factors, and properties related to performance are for the sealant and, where appropriate, for the bond of the sealant to its concrete substrate. ("Concrete substrate" refers to the hardened concrete surfaces to which the sealant must bond.) Back-up materials, primers, and incompatibilities of sealant with its concrete substrate (e.g., substrate moisture) are not covered - see references ACI 77a and PaC 84. Also, the problem of migration of plasticizers in sealants to substrate surfaces (examples of substrates include concrete, neoprene gaskets, EPDM gaskets, and bituminous materials) is not covered. (Section 1.2 describes which types of sealant materials are covered.)

(Continued)

Table 2 (Concluded)

[c] Properties are to be determined for the specific degradation factors (strain, temperature, moisture, etc.) which simulate in-service conditions. Properties are considered preliminary because their relationship to in-service performance needs to be established. Also see discussion of properties in sections 3.2 and 3.3 and use of the glass transition temperature in references Kar 68 and Kar 73.

[d] "Cycles" includes a single cycle or any fraction of a cycle; "rate" refers to the rate at which strain and stress are occuring within a given cycle.

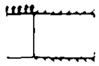
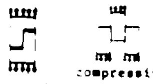
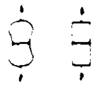
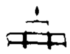
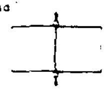
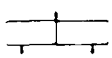
[e] Some sealants are required to be "self-leveling".

[f] See reference BuR 83 for a "pressure resistance" test method and requirement as well as other specifications for elastomeric canal joint sealer.

[g] The detrimental effects of the intrusion of solid foreign material in joints are discussed in reference ACI 77a.

Table 3

Standards, Specifications, and Investigations for Bond-Related Tests for Concrete Repair Materials

Bond-Related Tests[1]	Standards and Specifications: ASTM C 881-78[2] (ASTM 78c) C 1059-86[3] (ASTM 86)	Other Examples: United States	Other Examples: Japan	Other Examples: Germany	Investigations/Studies
Shear					
Direct 					ACI 77b[4], CBH 60, ChC 63, FuI 72, GPD 80[4], GPP 76, GPP 78, GrK 74, GSP 69, KrN 68, Pac 79, SCL 67, SeM 61, SIF 70, Spr 82, Spr 83a, Spr 83b, Spr 84a, Spr 84b, Spr 84c
Slant 	C 882-78[2] (ASTM 78d) C 1042-85[3] (ASTM 85)	AASHTO M 235-85I[2] (AAS 85) T 237-73[2] (1982) (AAS 73)			Bil 79, Bra 84, Joh 63, Joh 67, Joh 70, JSS 82, Kri 76, KrN 68, PaR, PIH 72, Tab 78, WSB 62
Other  "Push-Off" compressive double/ shear					ChL 77, ChL 78, Cho 60, Naw 84, Tsu 67,
Tension					
Uniaxial 		AASHTO T 237-73[2] (1982) (AAS 73)			Cho 60, CSP 84, GPP 76, GSP 69, Ino 76, PaR, PIH 72, SMP 81, Spr 82, Spr 83a, Spr 84b, WSB 62
Adhesion "Pull-Off" 		AASHTO T 237-73[2] (1982) (AAS 73) ACI ACI 503R-80[2] (ACI 80)		(HRS 78)[5]	Cau 84, DaB 78, Kra 67, LoM 84
Splitting 					Fat 83
"Point-Load" 					Sau 84 (Also see reference CRD 85)
Flexure 			JIS A 6024-1981[2] (JIS 81)		Cho 60, FaH 85, Fat 83, FuI 72, GPP 76, GSP 69, Hug 82, Ino 76, JoD 66, MaO 85, Oha 81, Oha 84, OkN 67, PaR, SIF 70, Tsu 67
Thermal Compatibility (see section 4.2.3.2)	C 884-78[2,6] (ASTM 78e)			(HRS 78)[5,7]	Can 67, Pes 81, Spr 82, Spr 84a, WFR 83, Whi 68 (Also see temperature cycling studies - GPD 80, GPP 76, GPP 78, Pac 79, SCL 67, Spr 82, Spr 84a, Spr 84b, WFR 83)
Shrinkage	C 883-80[2] (Effective Shrinkage) (ASTM 80b)				Ale 81, Pes 81, Whi 68

[1] Variations occurred in the geometry of the test specimen or application of the load or both for different standards, specifications, investigations, and studies - examples of test specimen geometries and loadings are shown.

[2] Epoxy-resin systems (see standards, specifications, and test method (ACI 80) for details)

[3] Latex bonding agents or systems (see standards and specifications for details).

[4] Denoted "shear bond" or "bond (shear)"; details on manner in which shear stress was applied not given.

[5] This "Bulletin" includes specifications and test methods.

[6] Temperature cycling in air.

[7] Temperature cycling in water, salt water, and air; adhesion tensile tests required as part of evaluation.

Table 4[a]

Performance Requirements, Degradation Factors, and Properties Related to Performance of Materials Containing Polymers[b] Used to Overlay Concrete and Repair Spalls and Dormant Cracks in Concrete

Performance Requirements and Associated Degradation Factors	Properties[c] Related to Performance
1. The repair material, its concrete substrate[d], and the bond of the repair material to its concrete substrate[d] must withstand *all in-service* stresses and strains including those resulting from: external loads, including sustained, static, dynamic, cyclic, vibrational, abrasive, erosive, and hydraulic; internal stresses and strains caused by volumetric changes (contraction or expansion of repair material relative to its concrete substrate or concrete substrate relative to repair material), including those caused by (a) curing of repair material, and (b) temperature cycling or moisture content cycling or both of repair material and its concrete substrate; and stresses and strains due to movement of structure (e.g., settlement).	1. (i) Strength of repair material, including tensile, compressive, shear, *torsional, flexural, and combinations of these* (e.g., *strength* when subjected to tensile and shear stresses). Fracture, impact, abrasion[e], erosion[e], and cavitation resistance of repair material. (ii) Strength of bond of repair material to its concrete substrate, including tensile, compressive, flexural, direct shear, torsional, slant shear, and combinations of these (e.g., bond strength when subjected to tensile and shear stresses). (Bond failure can occur at the bond interface, in the repair material, or in its concrete substrate.) (iii) Coefficient of thermal expansion, curing shrinkage, modulus of elasticity, poisson's ratio, creep, stress relaxation, and strain at ultimate stress of repair material. Resistance to volumetric changes of repair material relative to its concrete substrate (e.g., due to (a) curing shrinkage, and (b) temperature cycling or moisture content cycling or both).
2. When subjected to loading (e.g., sustained) or *elevated temperature* or both, repair material and the bond of the repair material to its concrete substrate must not deform excessively[f], soften, lose strength, or lose stiffness so as to cause a structural failure or loss of serviceability.	2. *Strength* (*see 1.*), *stiffness, and deformation under loading* (e.g., sustained) or high temperatures or both including (*a*) creep deformation and creep rupture of the repair material, including the interface of the repair material at its concrete substrate, and (b) modulus of elasticity of repair material. Glass transition temperature of polymer in repair material.
3. If structure is intended to prevent the passage of water then repair material and the bond of the repair material to its concrete substrate must resist the degrading effects of moisture and prevent the movement of water, including the following conditions: water immersion, splashing, wetting and drying, rain, condensation, snow, ice, freezing and thawing, and liquid pressure gradients. The ability of the repair material and the bond of the repair material to its concrete substrate to transmit water vapor may be required to prevent a moisture build-up *at or near the interface of the repair material and* its concrete substrate. This moisture build-up could result in failure (e.g., delamination of the repair material from its concrete substrate caused by frost damage to a non-frost resistant concrete substrate).	3. Liquid water absorption, and liquid water or water vapor transmission rates through repair material and along the interface of the repair material with its concrete substrate. Resistance of repair material, its concrete substrate, and the bond of the repair material to its concrete substrate to moisture effects (e.g., resistance to: temperature cycling in the presence of moisture, including freeze-thaw cycling; volume changes caused by moisture cycling; strength loss; stiffness loss; weight loss; and cracking, delamination, surface scaling, and popouts).

(Continued)

Table 5 (Continued)

Performance Requirements and Associated Degradation Factors	Properties[b] Related to Performance
4. Repair material, its concrete substrate (where applicable), and the bond of the repair material to its concrete substrate must not be adversely affected by aging, weathering, and other service factors under the range of service conditions including: temperature cycling (see 1.), temperature extremes (also see 2.), fire (including toxic gas or smoke evolution or both), moisture (see 3.), ultraviolet light (UV), chemical exposure, and biological exposure. If required, appearance of repair material must be acceptable.	4. Resistance of repair material, its concrete substrate (where applicable), and the bond of the repair material to its concrete substrate to: softening, strength loss, and excessive deformation (especially at elevated temperatures, including fire exposure also see 2.); brittleness (especially at low temperatures or high loading rates or both); moisture effects (see 3.); UV light effects; chemical effects (e.g., softening or weight loss); temperature cycling (thermal compatibility) of repair material and its substrate (see 1. (iii)); environmental, chemical, and other treatments (aging, temperature, UV light, moisture, etc.) - can also be performed prior to or during testing of the properties in this table; cracking, delamination, surface scaling, and popouts; biological effects; and smoke and gas evolution caused by fire or high temperature or both. Appearance-related properties (color matching, staining, texture, etc.).
5. Performance requirements and degradation factors related to reinforcing steel (bond to steel, protection of steel, corrosion reduction, etc.).	5. Not covered in this report.
6. Repair material has adequate skid or wear resistance or both.	6. Skid resistance and wear resistance of repair material.
7. Repair material, its concrete substrate, and the bond of the repair material to its concrete substrate must meet the appropriate requirements in this table prior to and during curing of the repair material. The repair material must develop an adequate bond to its concrete substrate. Also, the repair material and its bond to its concrete substrate must resist the adverse effects of incompatibilities of repair material with its concrete substrate, heat evolution, and blistering prior to and during curing of the repair material. If required, repair material must resist sagging prior to and during curing of the repair material.	7. Resistance of repair material, its concrete substrate, and the bond of the repair material to its concrete substrate to any adverse effects occurring prior to and during curing of the repair material, including adverse effects caused by shrinkage or heat evolution or both of repair material; chemical incompatibility of repair material with its concrete substrate; incompatibility of repair material with moisture on its concrete substrate; and blistering of repair material (see section 4.2.2) - also see other appropriate properties in this table. If required, resistance to sagging prior to and during curing of repair material.

[a] Although the information in this table covers many situations, it is not comprehensive. Therefore, each structure to be repaired needs to be carefully analyzed on an individual basis, choosing combinations of the appropriate entries of performance requirements, degradation factors, and properties related to performance from this table and adding any performance requirements, degradation factors, and properties related to performance as encountered or needed. The numerous sources used in the preparation of this table (e.g., ACI 77b, ASTM 82, Bil 79, Bul 80, DeP 81, FIP 78, Fur 84, ISO 84, Sca 84, Sch 80, Sch 82a, Sch 82b, War 84, Whi 68 and the standards and specifications given in table 3) contain further details.

[b] Included are: polymer adhesives, polymer mortars and concretes, and polymer-modified mortars and concretes. Polymer-impregnated concrete, bituminous materials, and materials containing sulfur are excluded.

(Continued)

Table 4 (Concluded)

[c] Properties are to be determined for the specific degradation factors (stress, temperature, moisture, etc.) which simulate in-service conditions. Properties are considered preliminary because their relationship to in-service performance needs to be established. Properties related to the concrete substrate are given when the repair material can cause its concrete substrate to fail. Also see discussion of properties in sections 4.2 and 4.3.

[d] The performance requirements of the repair material as related to its concrete substrate are that the repair material must not cause its concrete substrate to fail. "Concrete substrate" refers to the hardened (existing) portland cement concrete surface or surfaces to which the repair material is bonded. The repair material can be bonded above, below, or in between the concrete surface or surfaces repaired.

[e] See reference Ale 85 on the abrasion resistance of concrete and reference Liu 80 on the abrasion-erosion resistance of concrete.

[f] For example, Warner (War 84) cited an example of how excessive deformation in a repair material can result from a mismatch in the moduli of elasticity of the repair material relative to the concrete it is bonded to. This excessive deformation can cause a failure of the concrete.

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